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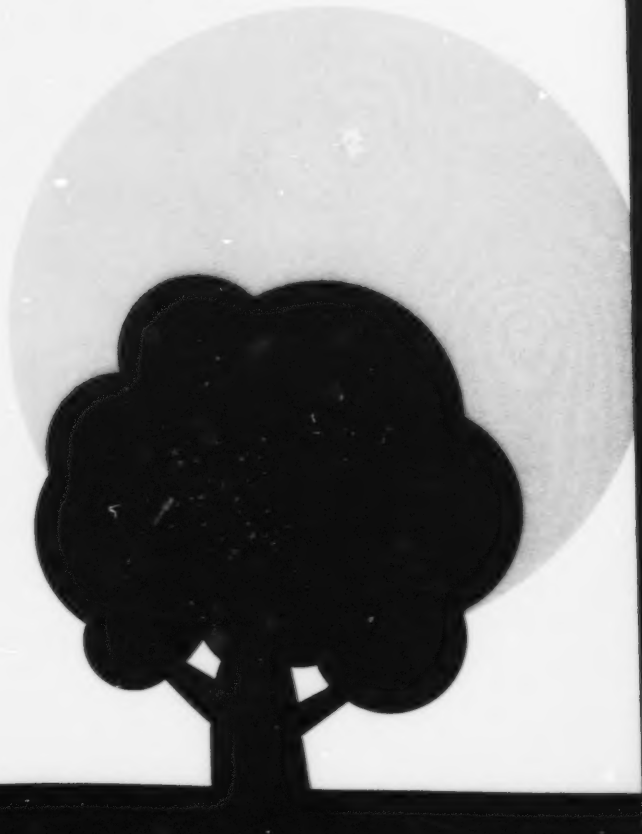

Canada

Superwindows from Pyrolytic Deposition of Fluorine Doped Tin Oxide on Glass. U-values and Electrical Contacts.

RENEWABLE ENERGY BRANCH

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Abstract

A thin film of fluorine doped tin oxide (SnO_2:F) on glass exhibits high electrical conductivity, high transmittance and low emissivity in the visible region of the light spectrum. Heating the glass is accomplished by making two separate electrical contacts on the thin film and applying a potential difference between them.

Electrical contacts to fluorine doped tin oxide coated glass were investigated for the purpose of producing low cost, electrically heated windows. The contact resistance between the film and the electrical contact and the stability of different contacts were compared. It was shown that the electrical contacts using Carbon Dag are essentially equivalent in electrical properties and performance to that of Silver Dag contacts. The low cost of Carbon Dag used with metal tape as the contact make it more attractive for developing electrically heated windows.

Thermal performance of different types of glazings was compared. Two SnO_2:F coated, double glazed, low-ϵ windows from Simon Fraser University (SFU) were measured for their thermal resistance at the National Research Council and were compared to low-ϵ, double glazed windows from other manufacturers. The heat loss coefficient (U-value) for the SFU double glazed, low-ϵ windows was found to be slightly higher than for similar windows from other manufacturers which could result from variations in the different measurement techniques. The optical

properties of SnO_2:F thin films on glass were also measured and compared.

AVANT-PROPOS

Une mince pellicule d'oxyde d'étain dopé au fluor (SnO_2:F) déposé sur un vitrage affiche une conductivité électrique élevée, une faible émissivité et une transmittance élevée dans le domaine visible du spectre. Le verre est chauffé en appliquant une tension électrique à deux contacts électriques distincts posés sur la pellicule.

On a examiné si, à partir de vitrages revêtus d'oxyde d'étain dopé au fluor et munis de contacts électriques, il est possible de produire des fenêtres chauffées électriquement, de meilleure qualité et peu coûteuses. La résistance de contact entre la pellicule et le contact électrique ainsi que la stabilité de différents contacts ont été comparés. Il en est ressorti que les contacts électriques composés de Carbon Dag présentent essentiellement les mêmes propriétés électriques et le même rendement que les contacts en Silver Dag. Cependant, le faible coût du Carbon Dag combiné à un ruban métallique offre plus d'avantages dans la fabrication de fenêtres chauffées électriquement.

Le rendement thermique des différents types de vitrage a fait l'objet d'une étude comparative. Au Conseil national de recherches, on a mesuré la résistance thermique de deux fenêtres double vitrage revêtu de SnO_2:F à faible émissivité provenant de l'Université Simon Fraser (USF); cette résistance a ensuite été comparée à celle des fenêtres double vitrage à faible E d'autres fabricants. Le coefficient de déperdition calorifique (valeur U) des fenêtres double vitrage à faible E était légèrement supérieur à celui des mêmes fenêtres d'autres

fabricants, mais cette différence a peut être été causée par des écarts de mesure entre les différentes techniques utilisées. Les propriétés optiques des minces pellicules de SnO_2:F sur du verre ont en outre été mesurées et comparées.

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Executive Summary

An optically transparent and electrically conducting thin film on glass can be heated and used to defog or defrost windows. Heating the glass can also provide radiant heating. A thin film of fluorine doped tin oxide (SnO_2:F) on glass exhibits high electrical conductivity, high transmittance and low emissivity in the visible region of the light spectrum.

Simon Fraser University has developed a method of applying a thin film of fluorine doped tin oxide on glass (SnO_2:F). This project was undertaken,

(1) to investigate the electrical contacts to SnO_2:F coated glass for producing low cost, better quality electrically heated windows;

(2) to study the thermal performance of the SnO_2:F coated windows with and without heating the glass electrically, and

(3) to measure the optical properties of SnO_2:F coated glazings.

Glass heating is accomplished by making two separate electrical contacts to the conducting film and applying a voltage. A current which is passed through the thin film causes heat to be dissipated across the window. Ideally, the electrical contacts to the thin film should be stable over long periods of time, should exhibit a low resistance and a high current capacity, and should be relatively inex-

pensive.

Electrical contacts to SnO_2:F coated glass were made with different combinations of conductive copper tape, tin-coated copper tape or tin-coated braided copper wire and Silver Dag or Carbon Dag (a commercial product of colloidal suspensions of silver or carbon). A combination of metal tape and Dag (a bridge between the conducting thin film and the current carrying metal strip) was found to give better results than the metal strip or Dag alone. The metal strip alone showed poor electrical contact and the Dag alone did not carry sufficient current and was also susceptible to cracking.

Tests for long-term stability and contact resistance of various elctrical contacts were performed. The best results were obtained with tin-plated copper foil in combination with Silver Dag or Carbon Dag. Although a braided wire and Silver Dag contact provides better mechanical strength of the terminals than the other contacts, it is undesirable since it uses a large quantity of Dag and a good contact between the wire and the SnO_2:F film is not established as easily as for the tape. Good mechanical strength at the terminals is important in applications where rough handling may lead to broken contacts. Copper tape in combination with Carbon Dag yielded a low contact resistance; however, the application of a potential difference over a long period of time caused a greenish-black coloration of the contact. This coloration was caused by an electrochemical reaction between the

copper and the solvent of the Carbon Dag. The use of tin-plated copper tape avoided the problem of coloration.

The thermal performance of windows with SnO_2:F coated glass was determined. Two SnO_2:F coated, low-ϵ, double glazed SFU windows were tested at the National Research Council in Ottawa. One of the SFU windows had a SnO_2:F film coated on the inner side of the interior glass (surface 3) while the other SFU window had both inner sides of the glasses coated (surfaces 2 and 3). The gap between the two glass glazings was 12.7 mm and the coating on the interior glass panel (surface 3) was used as an internal heater.

The coefficient of heat transmission (U) of the two SFU windows was compared with double glazed, low-ϵ windows from other manufacturers. The U-value for a non-heated SFU window was 2.50 W/(m^2K) as compared to 1.96 W/(m^2K) for a window manufactured by Glaverbel and 2.27 W/(m^2K) for windows manufactured by Ford or PPG. The heat transmission coefficient for the SFU windows was found to be slightly higher than the published U-values of similar windows from other manufacturers. This result could be due to different measuring techniques and varying test conditions; thus, a true comparison of the quoted U-values was not possible. Heating the SFU double glazed window by applying an electrical current to the internal heater increased the U-value to 2.70 W/(m^2K). This increase is expected since the heated film would increase the temperature of the air enclosed by the two

glass panes.

The optical and infrared properties of the SFU double glazed windows were measured and compared with those from several manufacturers. The SFU glass shows high infrared reflectance for wavelengths larger than 2.5 μm which is slightly lower than the Glaverbel glass. The high transmittance of the SFU glass in the visible region of the light spectrum (maximum at about 550 nm) results in a greenish tint.

The economic analysis showed that using Carbon Dag instead of Silver Dag would lower the cost of a low-ϵ, double glazed window by about 24 per cent.

RÉSUMÉ

Une mince pellicule transparente et électriquement conductrice déposée sur un vitrage peut être chauffée pour désembuer et dégivrer les fenêtres. En chauffant le verre, on réalise aussi un réchauffement par rayonnement. Une mince pellicule d'oxyde d'étain dopé au fluor (SnO_2:F) déposée sur un vitrage affiche une conductivité électrique élevée, une faible émissivité et une transmittance élevée dans le domaine visible du spectre.

L'Université Simon Fraser a mis au point une méthode pour l'application sur un vitrage d'une mince pellicule d'oxyde d'étain dopé au fluor (SnO_2:F). Ce projet avait pour objectif :

1) d'analyser si la pose de contacts électriques sur un vitrage revêtu d'oxyde d'étain dopé au fluor, permet d'obtenir des fenêtres chauffées électriquement de meilleure qualité et peu coûteuses;
2) d'analyser le rendement thermique des fenêtres revêtues de SnO_2:F lorsque leur vitrage est chauffé électriquement et lorsqu'il ne l'est pas; et
3) de déterminer les caractéristiques optiques des vitrages revêtus de SnO_2:F.

Le verre est chauffé en appliquant une tension électrique à deux contacts électriques distincts fixés à la pellicule conductrice. Le courant qui traverse la mince pellicule a pour effet de dissiper de la chaleur sur toute la surface de la fenêtre. Idéalement, les contacts électriques doivent être stables à long terme, et avoir une faible résistance et une grande conductivité électriques, en plus d'être relativement peu coûteux.

Des contacts électriques pour vitrage revêtu de SnO_2:F ont été fabriqués en combinant du ruban de cuivre conducteur, du ruban de cuivre revêtu d'étain ou du fil de cuivre tressé revêtu d'étain à du Silver Dag ou du Carbon Dag (produits commerciaux à base de suspensions colloïdales d'argent ou de carbone). En combinant un ruban métallique à un dag (pont entre la pellicule conductrice et la bande métallique d'alimentation en électricité), on a obtenu de meilleurs résultats qu'en les utilisant séparément. La bande de métal utilisé seule assure un contact électrique faible, tandis que le dag seul ne transmet pas suffisamment de courant et a tendance à se fissurer.

Des essais de stabilité à long terme et de résistance de contact ont été réalisés sur divers contacts électriques. Ce sont des feuilles minces en cuivre étamé combinées à du Silver Dag ou du Carbon Dag qui ont donné les meilleurs résultats. Bien que les contacts combinant fil tressé et Silver Dag offrent une meilleure résistance mécanique aux bornes que les autres contacts, il est préférable de ne pas les utiliser étant donné qu'ils nécessitent une grande quantité de dag et que le contact entre le fil et la pellicule de SnO_2:F n'est pas aussi facile à établir qu'entre le ruban et la pellicule. Il est important que la résistance mécanique des bornes soit satisfaisante parce que, dans certaines applications, la manipulation peut provoquer la rupture des contacts. Un ruban de cuivre combiné à du Carbon Dag a une faible résistance de contact; cependant, l'application d'une tension électrique s'est traduite après un certain temps par la coloration noir verdâtre du contact, due à la réaction électrochimique du cuivre avec le solvant du Carbon Dag. L'utilisation de ruban de cuivre étamé a éliminé ce problème de coloration.

Le rendement thermique des fenêtres à vitrage revêtu de SnO_2:F et d'autres types de fenêtres a été évalué. Deux fenêtres de l'USF à faible E et à double vitrage revêtu de SnO_2:F ont été soumises à des essais au Conseil national de recherches du Canada à Ottawa. La surface interne de la vitre intérieure (surface 3) d'une des deux fenêtres était revêtue d'une pellicule de SnO_2:F, tandis que les deux surfaces internes des vitres de l'autre fenêtre en étaient revêtues (surfaces 2 et 3). L'espacement des deux vitrages était de 12,7 mm et le revêtement du panneau intérieur (surface 3) a servi d'élément de chauffage.

Le coefficient de transmission thermique (valeur U) de ces deux fenêtres de l'Université Simon Fraser a été comparé à celui des fenêtres à faible E et à double vitrage revêtu d'autres fabricants. La valeur U d'une fenêtre de l'USF non chauffée a été de 2,50 $W/(m^2K)$, comparativement à 1,96 $W/(m^2K)$ pour une fenêtre fabriquée par Glaverbel et à 2,27 $W/(m^2K)$ pour celles fabriquées par Ford et PPG. Le coefficient de transmission thermique des fenêtres de l'USF s'est révélé légèrement supérieur aux valeurs U publiées pour des fenêtres semblables d'autres fabricants; cette différence peut être attribuable à l'application de techniques de mesures différentes et à des conditions d'essai variables. Il n'a donc pas été possible de faire une comparaison réelle des valeurs U obtenues.

Le réchauffement de la fenêtre de l'USF par sa mise sous tension a eu pour effet d'élever sa valeur U à 2,70 $W/(m^2K)$. Cette augmentation était prévisible étant donné que la pellicule chauffée devait faire augmenter la température de l'air emprisonné entre les deux vitrages.

Les propriétés optiques des vitrages de l'USF ont été déterminées et comparées à celles de plusieurs vitrages de série. Le vitrage de l'USF présente une réflectance élevée dans l'infrarouge pour les longueurs d'onde supérieures à 2,5 m, mais elle est légèrement inférieure à celle du vitrage Glaverbel. La transmittance élevée du vitrage de l'USF dans le domaine visible du spectre produit une teinte verdâtre.

L'analyse économique a indiqué que l'utilisation de Carbon Dag plutôt que de Silver Dag aurait pour effet de réduire d'environ 24 % le coût d'une fenêtre à double vitrage et à faible E.

Introduction

Thin films of doped tin(IV) oxide on glass substrates are of considerable technological importance. High electrical conductivity, transmission in the visible region of the light spectrum, and infrared reflecting properties of fluorine-doped tin oxide (SnO_2:F) films are utilized in heat reflecting windows, antireflection coatings on solar cells, and transparent electrode heating systems.

Thin films of SnO_2 on glass have been prepared by various techniques, such as spray pyrolysis[1-4], chemical vapour deposition (CVD)[5-7], sputtering methods[8,9], and evaporation[10,11]. The technique of spray pyrolysis under atmospheric pressure was found to be less expensive than other thin film deposition techniques. For example: AIRCO sells industrial sputtering facilities for approximately $4 M; a spray deposition facility which handles the same production volume would probably cost only one tenth as much as the sputtering facility. Commercial low-ϵ windows up to 3.5 m (12 ft). in width are now produced on a dedicated float line by Ford Glass in the U.S.A. and by various other processes by Glaverbel in Belgium and PPG in the U.S.A.. These companies sell glass panes for approximately Can.$19/$m^2$ ($1.70 / ft^2), wholesale price.

For the past 5 years the Energy Research Institute of Simon Fraser University has conducted research on fluorine doped SnO_2 films on soda glass under the sponsorship of NRC, B.C. Science Council, NSERC, and as

a subcontractor of an IRAP program with the largest tempering company in Western Canada (Tempa Industries, North Vancouver, B.C.). The deposition technique is by spray pyrolysis wherein an aqueous solution of $SnCl_4$ and SnF_2 is hydrolyzed at a hot glass substrate (400 to 500 °C)[12]. In the spraying process, illustrated in figure 1, the aerosol is generated ultrasonically to yield a uniform particle size, an important parameter for good film quality. As a result of this research a SnO_2:F coated glass was produced which exhibits better electrical and optical properties than the commercially available low-ϵ glass. In addition, a tempered, high strength laminated safety glass with high electrical conductivity was made; this product is of interest to manufacturers of aeroplanes and arctic ships and machinery.

A. Electrical Contacts

Optically transparent, conducting thin films on glass can be electrically heated and utilized to defog or defrost windows. The heating is accomplished by making two electrical contact strips to the thin film and applying a potential difference between the two contacts. The contacts should be stable over long periods of time and be relatively inexpensive. In addition, they should exhibit a low resistance and a high current capacity.

The contacts on commercially available "defrosting" windows are applied by various methods. Leybold-Heraeus of West Germany applies a silver contact by a silk-screening method. Ford produces the contact

also by an automated silk-screening technique wherein a silver enamel and low melting glass frit mixture is screened through a stainless steel grid and baked at 677 °C (1250 °F). The melting of the glass frit causes a good adhesion between the silver contact and the low-ϵ film.

Experiments designed to improve electrical contacts to SFU SnO_2:F coated glass and to test for contact deterioration with an applied heating current have yielded encouraging results. Past experience has shown that a commercial colloidal silver suspension (Electrodag #415 from Acheson Colloids Ltd. of Brantford, Ontario) applied to tin oxide films makes good electrical contacts.

An electrical contact utilizing Silver Dag is an appreciable expense in the manufacture of the windows, thus a cheaper alternative such as Carbon Dag (#154) a conducting colloidal suspension from Acheson Colloids Ltd. of Brantwood, Ontario would be desirable. The cost of Carbon Dag is about 40 times lower than Silver Dag. Similar considerations for *electrically heated* laminated windows for arctic ships, planes and automobiles, make Carbon Dag a desirable substitute to Silver Dag, provided that its electrical characteristics over appreciable times and adequate power loads are satisfactory. A survey of electrical contacts used in the window industry indicates that so far, Carbon Dag has not been considered as an appropriate contact cement.

Electrical contacts to SFU low-ϵ glass were made with a combination of conductive copper tape, tin-coated copper tape, or tin-coated braided

copper wire and Silver Dag or Carbon Dag. The technique used to apply the electrical contacts to the tin oxide films is essentially the same for all Dag / wire combinations. It is illustrated in figure 2 and described below for copper strips with Silver Dag:

Commercially available 3 mm or 6 mm wide copper strips with conducting adhesive on one of its sides were attached to opposing ends of the pyrolytically sprayed SnO_2:F glass. The Silver Dag suspension was applied manually onto the copper strips with some overflow (about 2 mm) onto the conducting SnO_2 thin film. Following a drying period, an epoxy layer was applied to cover both the copper strip and the Silver Dag. The combination of the copper strip and Silver Dag was found to give better results than the copper strip or the Silver Dag alone. The copper strip alone did not make a good enough electrical contact to the tin oxide probably due to the adhesive layer between the film and the copper. The Silverdag did not carry enough current and was susceptible to cracking. Applying Carbon Dag instead of Silver Dag by the same method as descibed above yielded similar results; thus, both colloids have to be supported by metal foil for adequate current capacity and by epoxy for sufficient mechanical strength.

The results from experiments performed using the two colloidal suspensions are presented in Figures 3 and 4, and in Table I. All experiments were performed on glasses from the same stock. The current was measured as a function of applied voltage and the resistance was found from the inverse slope of the current / voltage characteristics. To determine the contact resistance of the SnO_2:F thin film, a rectangular

piece of glass was used with copper foil and Silverdag as contacts at various distances away from one edge. The resistance was measured as a function of separation between contacts and is shown in figure 5. The y-intercept yields the contact resistance and the slope yields a quantity proportional to the SnO_2:F sheet resistance. The contact resistance of the copper foil with Silverdag was experimentally determined to be in the range of 0.1 to 0.8 ohms while the sheet resistance was found to be $34.5 \pm 0.7\ \Omega$.

Figure 3 shows the lowest sheet resistance for braided wire with Silver Dag while, braided wire with Carbon Dag yields the highest sheet resistance (23 % difference with respect to the Silverdag / braided wire contact). The Carbon Dag suspension is not as easily applied to the braided wire and thus the contact between the SnO_2:F and the wire is not easily established. Therefore, the contact resistance becomes appreciable yielding a higher total resistance. It should be noted that all experimental points plotted to yield the graph of figure 3 were obtained after applying a potential difference for periods up to 20 hours. From the lack of scatter in the data it may be inferred that there is long term stability in the contacts. Figure 4 shows results obtained after applying a potential difference of 20 V for one week. The highest resistance was obtained using copper foil with Silver Dag, while the lowest was obtained using tin-plated copper foil with Silver Dag, as well as copper foil with Carbon Dag. An examination of the $R_\square$ values derived from the data shown in figure 4 (see Table I) indicates that the smallest contact resistance was obtained with a tin-plated copper foil /

Silver Dag contact.

A drawback with the use of Carbon Dag and copper foil is that the aging process produces a discoloration. The contact turns green and green-black with the application of a potential difference over long periods of time. This colour change is due to an electrochemical reaction between the Carbon Dag and the copper. The electrical behaviour of the contact is not affected; however, the colour change may be an undesirable characteristic in certain applications where aesthetics are considered. The problem is avoided by using tin-plated copper foil.

B. U-Value Determinations for Double Windows

To determine the energy efficiency of electrically heated windows and to simultaneously test the adequacy of the electrical contact, eight double sealed windows were assembled at Tempa Industries Ltd. of North Vancouver. A schematic diagram of a double glazed window is presented in figure 6. All windows consisted of two 5 mm glass sheets with an area of 0.92 x 0.92 m^2 (3 x 3 ft^2), separated by a 12.7 mm air gap by means of aluminum spacers around the edges. The glass panes (Ford glass) were coated pyrolytically[12] at SFU with SnO_2:F at 450 °C except where indicated. The windows were divided in four groups:

Group 1. Two windows had a SnO_2:F coating on the inner side of the glass panel exposed to the warmer environment (surface 3).

Group 2. Two windows had a SnO_2:F coating on both inner sides (surface 2 & 3). Electrical contacts for heating were applied

to surface 3 using tin-plated copper braid with Silver Dag as contact cement since only two windows could be measured at NRC and the contact between Silver Dag and the SnO_2:F films was slightly superior over Carbon Dag contacts. The contact work was carried out at SFU. The heated glass panel would normally face to the interior, while the SnO_2:F film on surface 2 would serve as a heat reflector.

Group 3. Two windows had no coating on the glass and served as controls.

Group 4. The remaining two windows were essentially the same as the units of group 1; however, the SnO_2:F coated glass panes were from by PPG and Glaverbel.

The coefficient of heat transfer (U) was measured for one window of group 1 and one window of group 2 . For the group 1 window U was found to be 2.50 and 2.56 $Wm^{-2}K^{-1}$ for an inside temperature of 21 °C and outside temperatures of -18 °C and -35°C, respectively. The U-values for soft-coated, low-ϵ, double glazed windows (vacuum deposited metal film) from other suppliers (PPG, FORD) were measured at NRC a few months earlier and gave very similar values as the SFU windows. This result is very encouraging since soft-coated windows (sputtered metal films) generally have better heat reflecting properties and thus a lower coefficient of heat transfer than hard-coated windows (pyrolytic films)[13]; however, the soft-coated films have lower stability against oxidation and scratching.

Table II shows the U and R values for hard-coated (pyrolytic method) double glazed windows from SFU and other manufacturers[13]. The SFU double glazed window has the highest U-value; we expected it to be lower since our thin films show high reflectance in the infrared spectrum. These discrepancies in the U-values are likely to arise from the conditions under which the individual U value measurements were made, such as the wind speed during measurement (convection currents), glass panel thickness, and frame effects.

Heating the group 2 window was affected by passing a current through the thin film. The electrical resistance of the heater, which was composed of tin-plated copper braid with Silver Dag contacts and the thin film, was found to be 34.3 Ω at ambient temperature and 29.1 Ω at 31.1 °C with a maximum voltage applied of 30 Volts. The resistance decreased as the temperature of the thin film increased. With 48 Watts of power for 26 hours the resistance was 19.5 Ω and with 70 Watts of power the resistance was 16.3 Ω. The U values for the group 2 windows were found to be 2.70 and 2.78 $Wm^{-2}K^{-1}$ for an inside temperature of 21 °C and outside temperatures of -18 °C and -35 °C with 48 Watts and 70 Watts of power supplied to the heater, respectively. An increase in U is expected since the heated SnO_2:F thin film increases the temperature of the air in the gap. However, the heat loss through the outer glass pane is reduced by the SnO_2:F coating on surface 2.

C. Optical Properties of Thin Films

The spectral response of the infrared reflectance Fig.7) and the visual transmittance (Fig. 8) are presented for SnO_2:F coated glass from SFU and from various other manufacturers. Figure 7 shows a steep onset of infrared reflectance at about 5500 cm^{-1} (1.8 μm) for the Glaverbel and SFU thin films while the Ford, PPG and St. Gobain thin films reveal a more gradual infrared reflectance increase with decreasing wavenumbers. The SFU and Glaverbel films show the highest infrared reflectance for photon energies below 4300 cm^{-1} (wavelengths greater than 2.5 μm). The Glaverbel SnO_2:F glass exhibits the highest infrared reflectance ($\approx$ 90 %) for photon energies above 1000 cm^{-1} (10 μm). It is closely followed by the much thinner SFU film while the PPG and St. Gobain glass exhibit the lowest reflectance of about 66 - 70 %. The variations in infrared reflectance arise from dopant concentrations and film thickness as well as the different manufacturing processes. The Glaverbel and Ford SnO_2:F films are produced by a float glass method and the St. Gobain thin film is produced by a powder deposition method. The PPG glass has a SnO_2 coating on both surfaces and presumably is spray deposited from an organometallic solution containing tin.

The visible transmittance of the various SnO_2:F coated glasses (Fig. 8) fluctuates between 68 and 92 %. The observed visible transmittance differences between low-ϵ glasses from SFU and other manufacturers can be partly accounted for by differences in film thicknesses (see

TABLE II); the oscillatory behaviour arises from multiple interference caused by the thin film / glass interface. The SFU SnO_2:F coated glass shows high transmittance in the region of maximum eye sensitivity (550 nm) with a maximum of about 91 % at 580 nm, thus it has a slightly greenish appearance. The Glaverbel glass shows the lowest transmission spectrum of all films analyzed with an average transmittance of about 80% and a greenish-brown appearance. This seems to be correlated to its comparatively large film thickness (0.82 μm; see TABLE II). The Ford glass has a relatively uniform transmission spectrum over most of the visible range since the film is very thin. Its transmission is about 8% higher than that of the PPG thin film and has a bluish tint in reflection.

Conclusions and Recommendations

A combination of tin-plated copper tape and a silver colloidal suspension (Silver Dag) was found to yield the lowest contact resistance. This combination was found to be stable over long periods of time and able to carry high current capacity. A much cheaper substitute to Silver Dag which showed comparable characteristics was Carbon Dag. However, Carbon Dag in combination with copper tape produced a discoloration of the contacts due to an electrochemical reaction with copper. Using tin-plated copper tape instead of bare copper tape eliminated the problem of discoloration and its low contact resistance together with its low cost make it attractive for windows.

The heat loss coefficient (U value) of double glazed low-ϵ windows from SFU was measured at NRC in Ottawa. The U-values are higher than expected when compared to other manufacturers' U-values. The most probable reason for this result is that the experimental conditions such as wind speed (convection) and frame effects to determine the U-values varied, thus a direct comparison could not be made. The U-value of a conventional double glazed window is 2.84 $Wm^{-2}K^{-1}$ [13]. The low-ϵ coating reduces the heat transfer by 20 % for the Ford and PPG double glazed windows and 33 % for the Glaverbel window.

The cost of a double glazed window, composed of two 1 m^2 glass panels with a glass thickness of 5 mm with a 10 mm air gap and aluminum spacers is about \$64.00 (\$6.00 / ft^2). If one of the glass panes is coated with a heat reflecting fluorine doped tin oxide film, the wholesale costs will increase approximately \$16 / m^2 (\$1.50 / ft^2) to a total price of about \$80 / m^2 (\$7.50 / ft^2) or 1.25 times the cost of the conventional double glazed window. To produce an *electrically heated* window, the labour needed (approximately 4 hours) to make the electrical contacts to the SnO_2 film doubles the price to \$ 160 / m^2 (\$14.00 / ft^2). Further, the cost of the Silver Dag adds approximately \$53 / m^2 (\$5.00 / ft^2) to the total price. Thus the price for a 1 m^2 SnO_2:F coated double glazed window with electrical contacts based on Silver Dag for defogging or defrosting is \$213 (\$19 / ft^2). Using Carbon Dag instead of Silver Dag would lower the cost for a low-ϵ double glazed window to \$161 / m^2 (\$14 / ft^2), a cost reduction of 24% .

In summary, Carbon Dag in combination with a tin-coated copper foil is a suitable contact to SnO_2:F coated glass for the purpose of defogging or defrosting windows. Heating the interior pane of a double glazed low-ϵ window increases the heat transfer from the inside to the outside only slightly and would thus be acceptable as a combination of defrosting (defogging) and energy efficient windows. Using triple glazed heated windows would be desirable in areas of extreme winter temperatures.

Double windows filled with Argon gas or a combination of Argon and SF_6 gas instead of air may yield better U-values and more effective sound proofing. SFU has received, free of charge, from Drs. W. Peterson and D. Taylor of Repla Ltd. (Oakville, Ontario) gas filled low ϵ windows (using our SnO_2:F coated glass) for testing. The U-values will be determined as soon as a test apparatus for measurement of U-values in our laboratory is completed. We will use the NRC U-values as standards to determine relative U-values.

Communications

We have presented two talks on electrically heated windows and electrochromic windows as applied to transportation vehicles at the 1987 Society of Automobile Engineers (SAE) Conference and Exposition on Future Transportation Technology held on Aug. 10-13, 1987 in Seattle, Washington and at the Canadian Engineering Society Meeting in Vancouver, on January 17th, 1988 . Also, a paper[14] entitled: "Electrically Heated

Windows and Electrochromic Windows for Transportation Vehicles" was published in the SAE Technical Paper Series.

Through the Canadian Consulate in West Germany (R. Kosciuw) information was obtained that Leybold-Heraeus in Hanau, West Germany is actively involved in making electrical contacts to conducting thin films. The company leads the field of sputtered ZnO/Ag/ZnO films which are the strongest competitors for SnO_2:F films, both for "superwindows" and *electrically heated* laminated (curved) automobile glass. Leybold-Heraeus is also a leader in the research field of making stable electrical contacts to glass. Dr. Colbow visited Leybold-Heraeus last September and negotiations for an exchange of information and a possible joint venture for electrically heated windows in Canada are in progress.

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TABLE I. Resistance Measurements for Various Contacts.

CONTACT DESCRIPTION	$R_{[]}$* (ohm/□) (±0.1Ω)	WINDOW SIZE (cm^2)
Braided Wire and Silver Dag	35.1	20 X 30
Braided Wire and Carbon Dag	43.1	"
Copper Foil and Silver Dag	36.7	"
Tin-plated copper foil and Silver Dag	35.2	"
After one week of applying 20 volts		
Copper Foil and Silver Dag	37.6	14 X 20
Copper Foil and Carbon Dag	35.0	"
Tin-plated Copper Foil and Silver Dag	34.8	"
Tin-plated Copper Foil and Carbon Dag	36.9	"

* Includes contact resistance which is on the order of 1 Ω for the various contacts except for braided wire with Carbon Dag.

TABLE II. Comparisons of Double Glazed Low-ϵ Windows from Different Manufacturers

Company Name	Film Thickness (μm)	Resistance $\Omega/\square$	U-value[1,2] ($Wm^{-2}°K^{-1}$)	R-value[2] $ft^2h°F(BTU)^{-1}$	ϵ[2,3]
SFU	0.37	16.9	2.50[4]	2.27	----
GLAVERBEL	0.82	16.3	1.96	2.9	0.15
ST. GOBAIN	0.17	56.3	----	----	----
FORD	0.097	36.6	2.27	2.5	0.35
PPG (label)	0.075	55.5	2.27	2.5	0.31
(opposite)	0.17	36.8			0.31

[1] Conversion Factor from $m^2°KW^{-1}$ to $ft^2h°F(BTU)^{-1}$ is 5.67

[2] Reference 13: U-values given for Glaverbel, Ford and PPG are for double glazed low-ϵ windows consisting of two 3.2 mm ($^1/_8$") thick glass panes, one of the panes pyrolytically coated with tin oxide, and separated by a 12.7 mm ($^1/_2$") air space . The inside and outside temperatures were 21 °C (70 °F) and -18 °C (0 °F) respectively and the wind speed was 24 kph (15 mph). The glass area was considered without frame effects.
The SFU window uses 5mm thick glass panes and the same air space and temperature specifications as above.

[3] Emissivity.

[4] NRC measurement, October 1987.

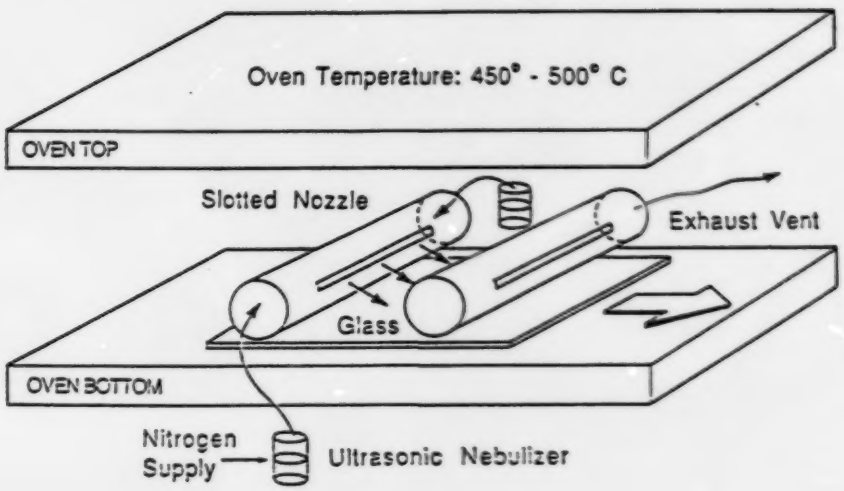

Figure 1. Apparatus used for pyrolytic spray deposition of tin oxide on glass.

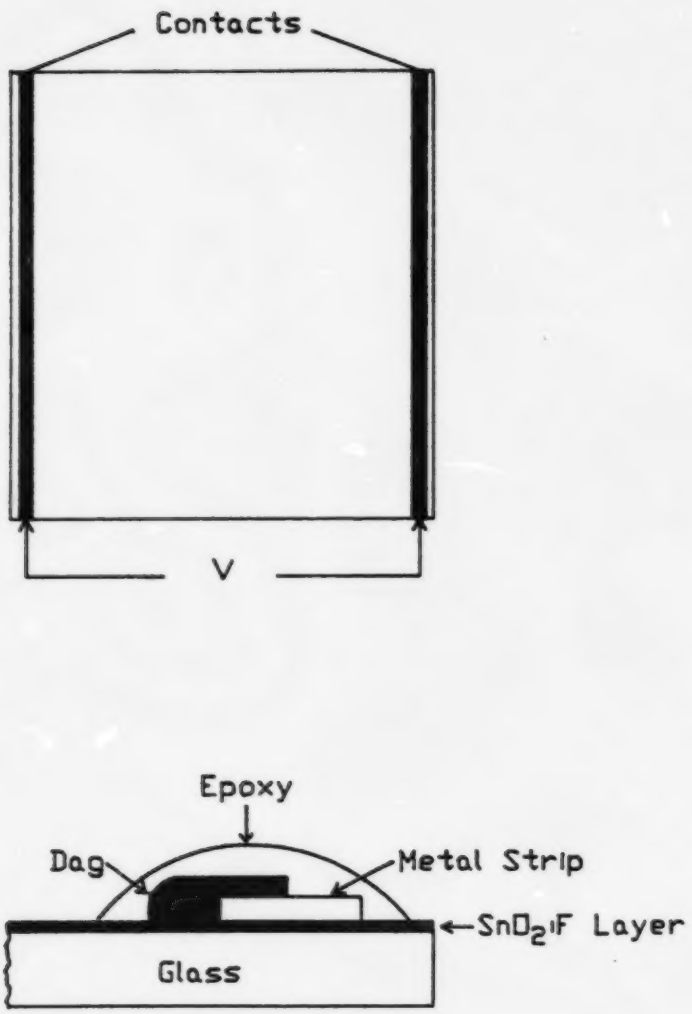

Figure 2. Illustration of electrical contacts to tin oxide coated glass.

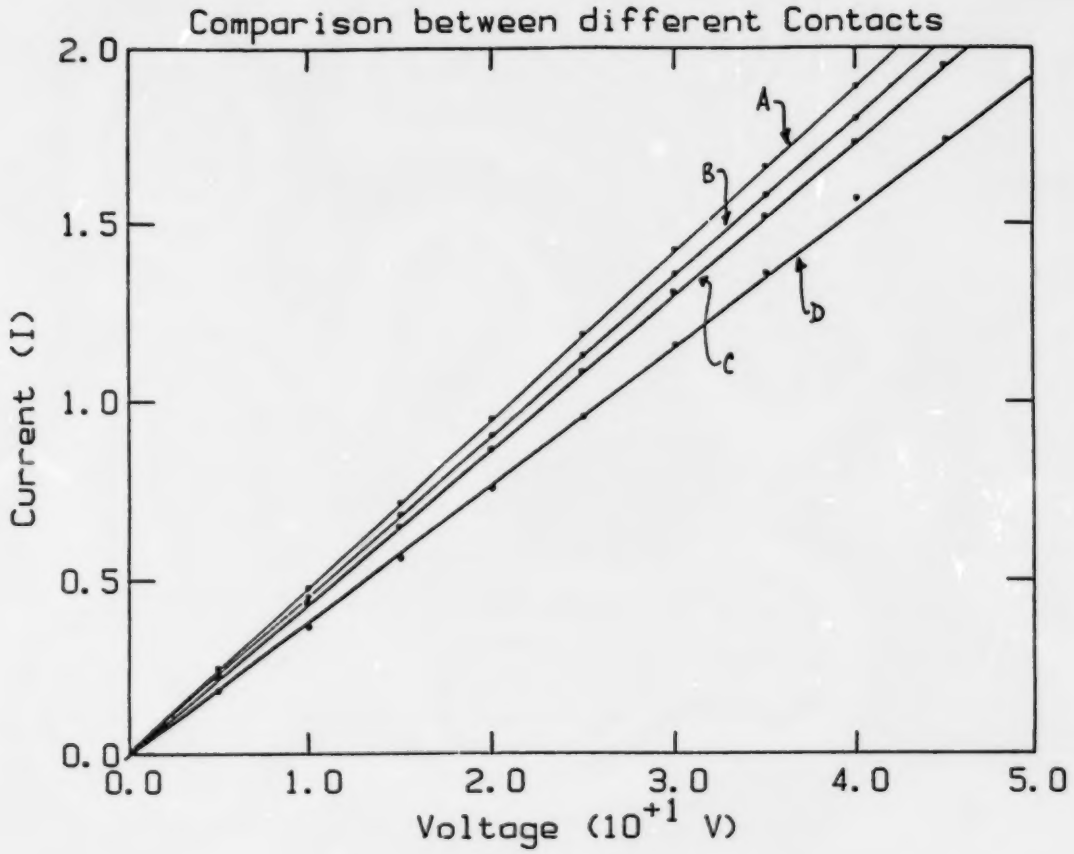

Figure 3. I-V characteristics of the various contacts: A) Braided wire with Silver Dag; B) Tin-plated copper foil with Silver Dag; C) Copper foil with Silver Dag; D) Braided wire with Carbon Dag.

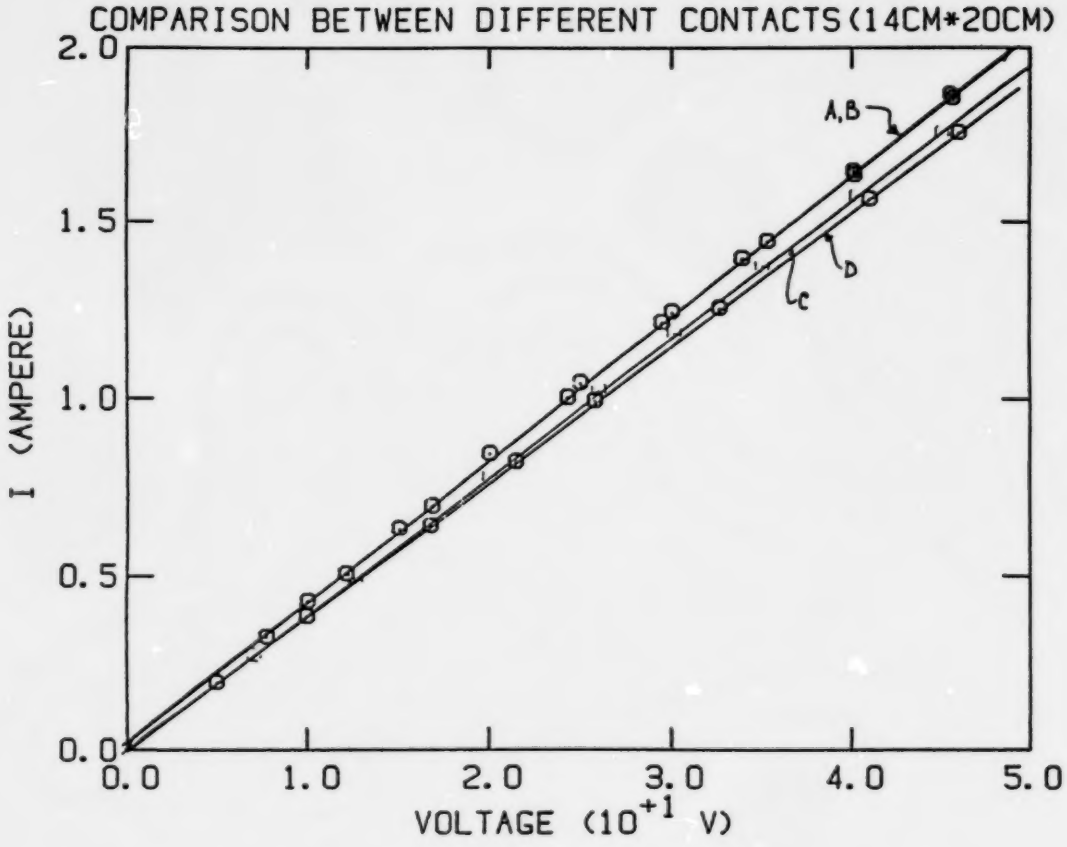

Figure 4. I-V characteristics of the various contacts after applying 20 volts for a period of one week: A) Tin-plated copper foil with Silver Dag; B) Copper foil with Carbon Dag; C) Tin-plated copper foil with Carbon Dag; D) Copper foil with Silver Dag.

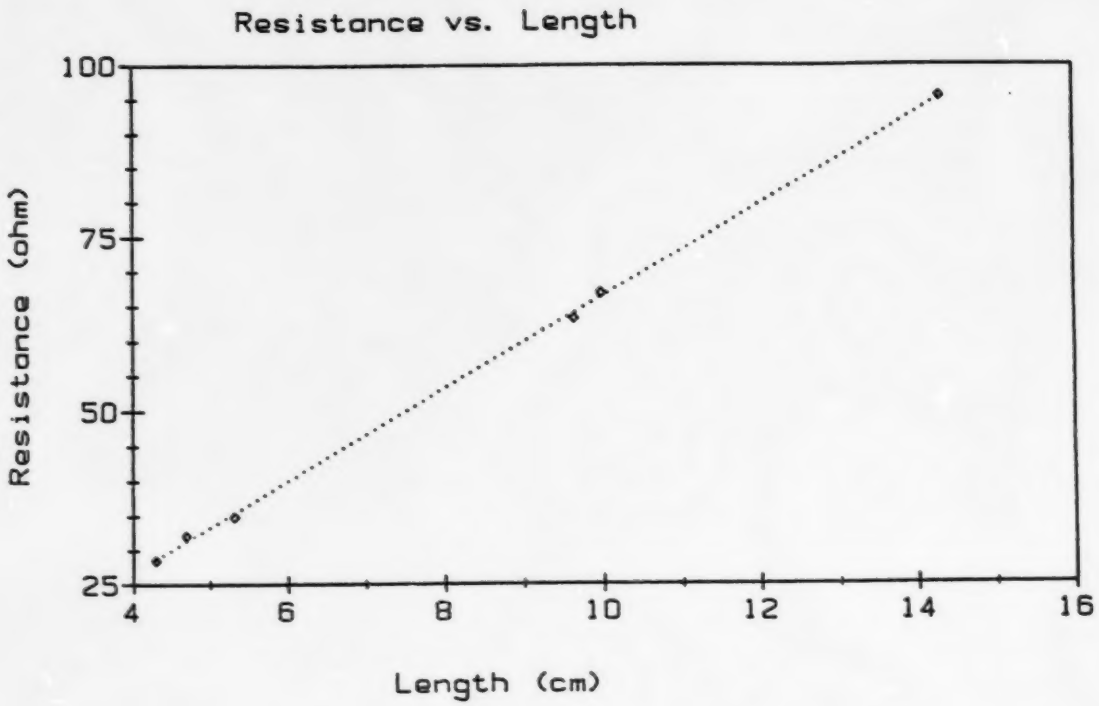

Figure 5. The effect of total resistance (contact and sheet resistance) on contact separation for a SnO_2:F thin film.

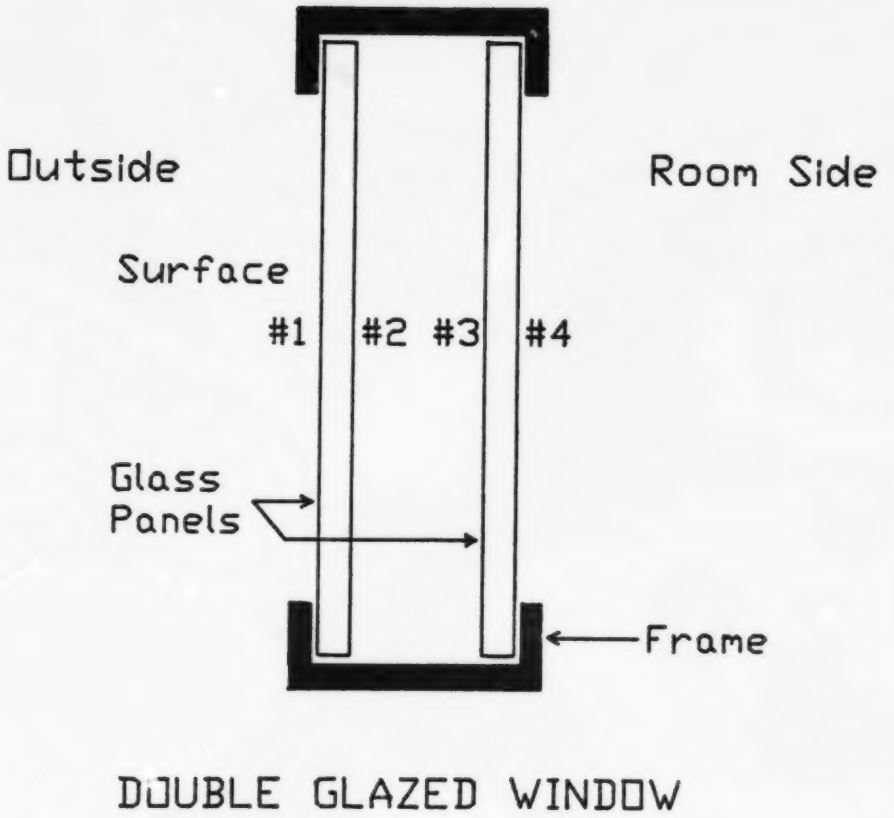

Figure 6. A schematic diagram of a double glazed windows.

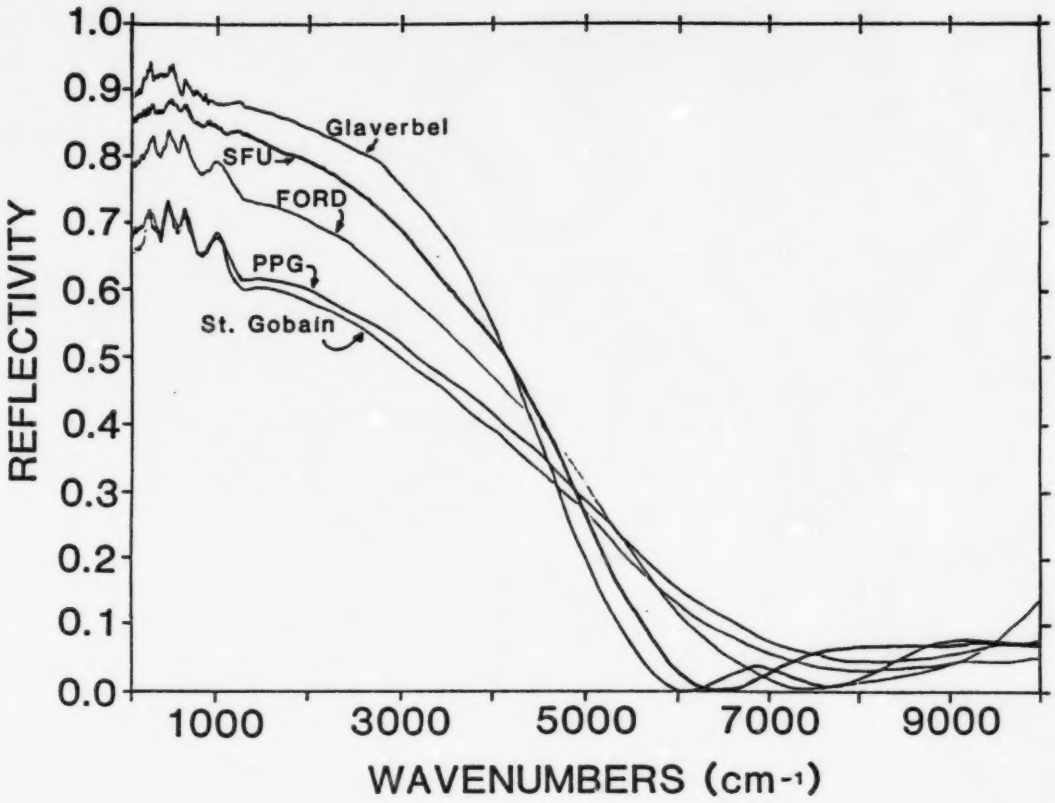

Figure 7. The spectral response of the infrared reflectance for SnO_2:F thin films from various manufacturers.

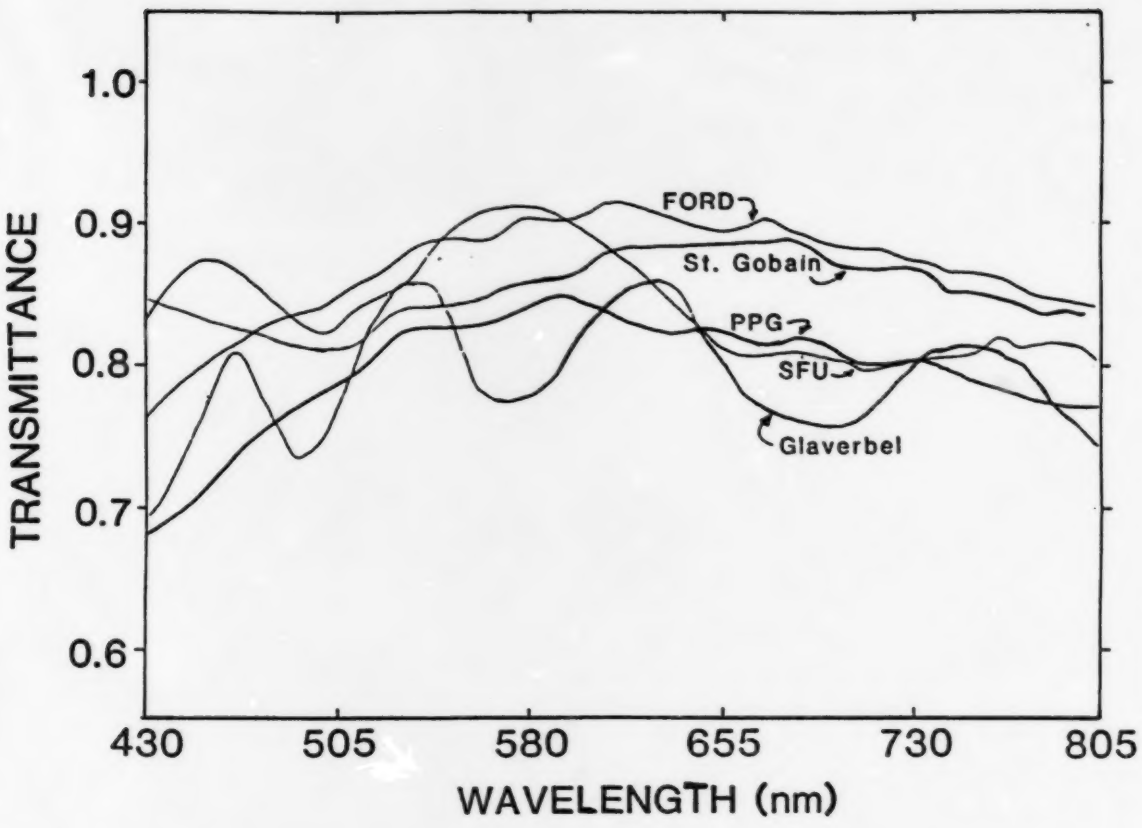

Figure 8. The spectral response of the optical transmittance for the films shown in Figure 4.

National Research Council Canada
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Institut de recherche en construction

CLIENT REPORT

for

SIMON FRASER UNIVERSITY
Burnaby, B.C.

Determination of the R-value of two glazing units:

- **Factory Sealed Double Glazed (FSDG) unit with low emissivity coating**
- **experimental FSDG unit with internal electric heater**

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W.A. Dalgliesh
Head, Quality Assurance

Report No: CR5475.1
Report date: 18 September 1987
Contract No. CR5475
Reference: Application for test dated 31 March 1987
Section: Building Services

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Canada

1. Summary:

Tests were conducted in the Environmental Test Facility of the Institute for Research in Construction to determine the heat transmission and thermal resistance values for two Factory Sealed Double Glazed units. Surface temperatures were also measured to give an indication of the condensation potential.

2. Test Specimens:

Glazing Unit #1: A 36 inch by 36 inch (0.916 m * 0.916 m measured) Factory Sealed Double Glazed unit of 5 mm glass thickness and low emissivity coating on one surface. The two sheets of glass are separated by a metal spacer of 12.7 mm nominal thickness.

Glazing Unit #2: A 36 inch by 36 inch (0.914 m * 0.914 m measured) Factory Sealed Double Glazed unit of 5 mm thick glass separated by a metal spacer of 12.7 mm nominal thickness. The internal electric heater is placed close to the metal spacer and the leads exit the unit at the top, one lead at each corner.

3. Test Procedure:

The standard test procedure is described in Appendix A. This procedure is valid for the tests on Glazing Unit #1. Modifications to this standard test procedure were made to analyse test results on Glazing Unit #2. These modifications are given in Appendix B.

4. Test Conditions:

Prior to testing, the calorimeter was purged with dry air and the room side chamber was dehumidified to reduce the relative humidity in the calorimeter box to avoid condensation on the glazing. During testing, the calorimeter air temperature was maintained at approximately 21°C. The weather side air temperature was set at -18°C and -35°C, as required. The pressure difference across the test assembly was kept to less than 3 Pa during the tests. The weather side air movement was established through use of a wind machine that directs the air perpendicular to the test specimen and providing a film coefficient of about 22 $W/(m^2 \cdot K)$.

The tests performed were as follows:

Glazing Unit #1
Test #1.1 at 21°C (room side air), and -18°C (weather side air)
Test #1.2 at 21°C (room side air), and -35°C (weather side air)

Glazing Unit #2
Test #2.1 at 21°C and -18°C with 48.7W supplied to internal heater
Test #2.2 at 21°C and -35°C with 70.1W supplied to internal heater

After each of tests 2.1 and 2.2, the internal heater was shut off to determine the change of glazing temperatures with and without power to internal heater.

5. Test Specimen Preparation and Instrumentation:
Glazing Unit #1 was mounted into the 0.920 m * 0.920 m opening of the mask to a depth of 53 mm from the room side of the vertical surface of the 129 mm deep mask. The full perimeter of the test specimen was sealed with plastic tape on the room side and on the weather side.

Thermocouples were mounted with aluminum foil tape to the exposed glazing on the room side and on the weather side. The thermocouple locations are shown on Figure 1.0.

Glazing Unit #2 was mounted, instrumented, and sealed as above. The leads for the internal electric heater were run from the top corners of the specimen along the room side face of the mask and out of the Environmental Test Facility to an external electric power supply, see Appendix B. The thermocouple locations are shown on Figure 2.0.

6. Results:
Table 1 lists the results of the thermal resistance and heat transmission for each test condition for Glazing Unit #1. Figures 1.1 and 1.2 show the surface temperatures for each test condition.

Table 2 lists the results for Glazing Unit #2 and Figures 2.1 and 2.2 show the surface temperatures and power supplied to the internal heater, with and without power supplied to the internal heater.

TABLE 1

Glazing Unit #1: See Test Procedure in Appendix A

Test Specimen:	units	symbol	TEST #	
			1.1	1.2
Mean Weatherside Air Temperature	°C	T_c	-18.1	-34.9
Mean Roomside Air Temperature	°C	T_h	21.0	21.0
Mean Baffle Temperature	°C	T_b	21.2	21.3
Mean Roomside Surface Temperature of Specimen	°C	T_1	8.9	3.7
Mean Weatherside Surface Temperature of Specimen	°C	T_2	-13.9	-28.7
Total Heat Flow Through the Test Assembly	W	Q_T	140.9	202.9
Heat Flow Through the Mask	W	Q_m	63.0	87.9
Heat Flow Through the Test Specimen	W	Q_s	77.9	115.0
Heat Flow Through Unit Area of Test Specimen	W/m^2	q_s	92.1	135.9
Temperature Difference (Surface to Surface)	K	T_1-T_2	22.8	32.4
Test Specimen Conductance	$W/(m^2 \cdot K)$	C	4.04	4.19
Resistance of the Test Specimen	m^2K/W	R	0.25	0.24
Roomside Air Film	$W/(m^2 \cdot K)$	fi	7.56	7.76
Weatherside Air Film	$W/(m^2 \cdot K)$	fo	21.8	21.8
Design Resistance of the Test Specimen	m^2K/W	R_D	0.40	0.39
Design Coefficient of Heat Transmission Through the Test Specimen	W/m^2K	U_D	2.50	2.56

TABLE 2

Glazing Unit #2: See Test Procedure in Appendix B

Test Specimen:	units	symbol	TEST #	
			2.1	2.2
Mean Weatherside Air Temperature	°C	T_c	-18.0	-35.0
Mean Roomside Air Temperature	°C	T_h	21.0	21.0
Mean Baffle Temperature	°C	T_b	21.1	21.2
Mean Roomside Surface Temperature of Specimen	°C	T_1	12.5	7.9
Mean Weatherside Surface Temperature of Specimen	°C	T_2	-13.7	-28.9
Total Heat Flow Through the Test Assembly	W	Q_T	113.1	164.3
Heat Flow Through the Mask	W	Q_m	62.8	88.1
Heat Flow Through the Test Specimen	W	Q_s *	50.3+48.7 = 99.0	76.2+70.1 = 146.3
Heat Flow Through Unit Area of Test Specimen	W/m^2	q_s	117.0	172.9
Temperature Difference (Surface to Surface)	K	T_1-T_2	26.2	36.8
Test Specimen Conductance	$W/(m^2 \cdot K)$	C	4.47	4.70
Resistance of the Test Specimen	m^2K/W	R	0.22	0.21
Roomside Air Film	$W/(m^2 \cdot K)$	fi		
Weatherside Air Film	$W/(m^2 \cdot K)$	fo		
Design Resistance of the Test Specimen	m^2K/W	R_D	0.37	0.36
Design Coefficient of Heat Transmission Through the Test Specimen	W/m^2K	U_D	2.70	2.78

Note: T1 and T2 are Area Weighted Average Temperatures.
* Heat Flow Through Test Specimen = Total Heat Flow - Heat Flow Through Mask + Power Supplied to Internal Heater.

Figure 1.0

Room-side View of the Factory Sealed Double Glazed Unit #1 Showing the Locations of the Thermocouples on the Exposed Glazing and at the Spacer.

Dimensions in millimeters

Scale: 1 = 5

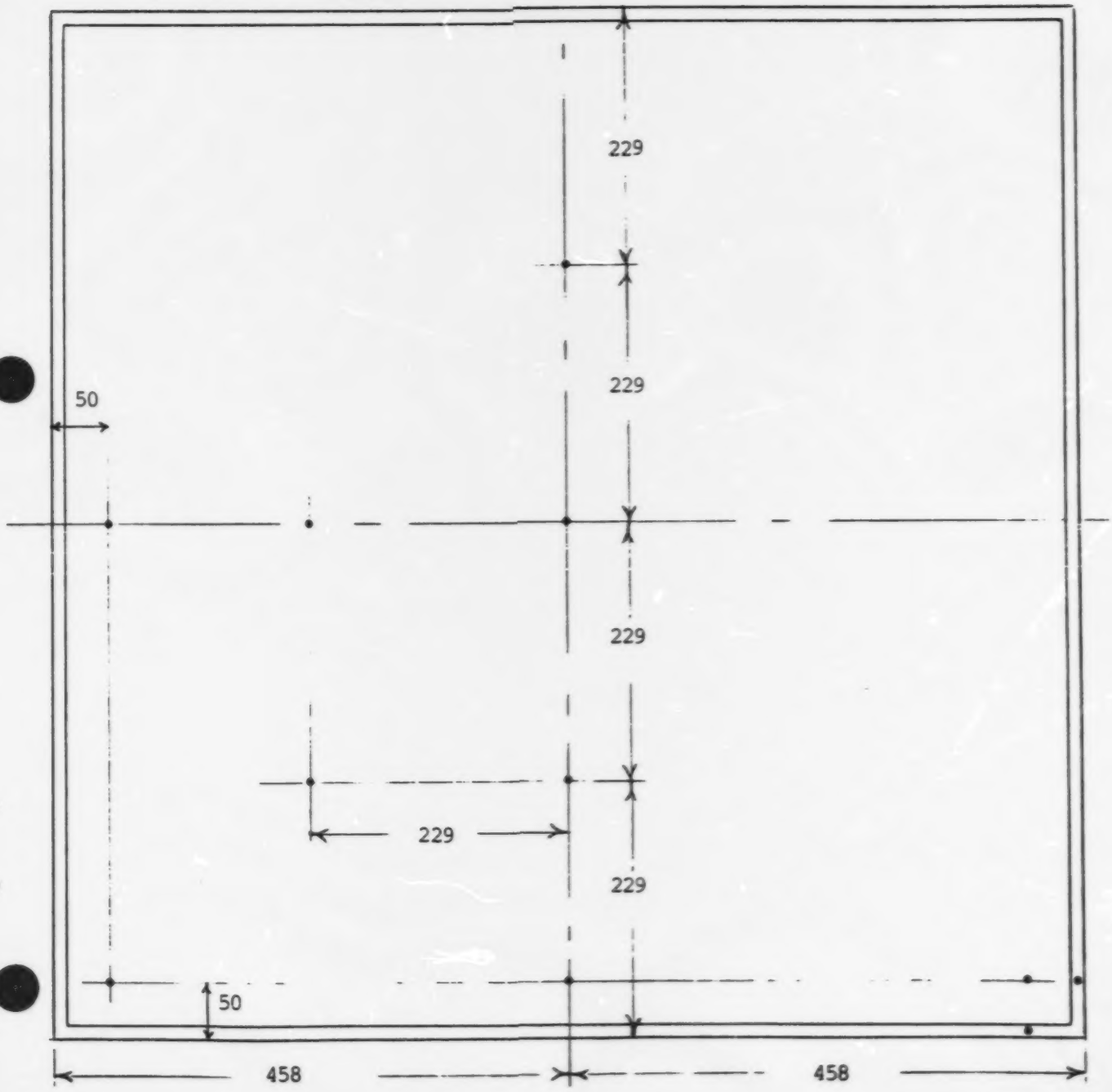


Figure 1.1

Glazing Unit #1:
Temperatures at Locations Shown on Figure 1.0
Test #1.1: 21°C/-18°C

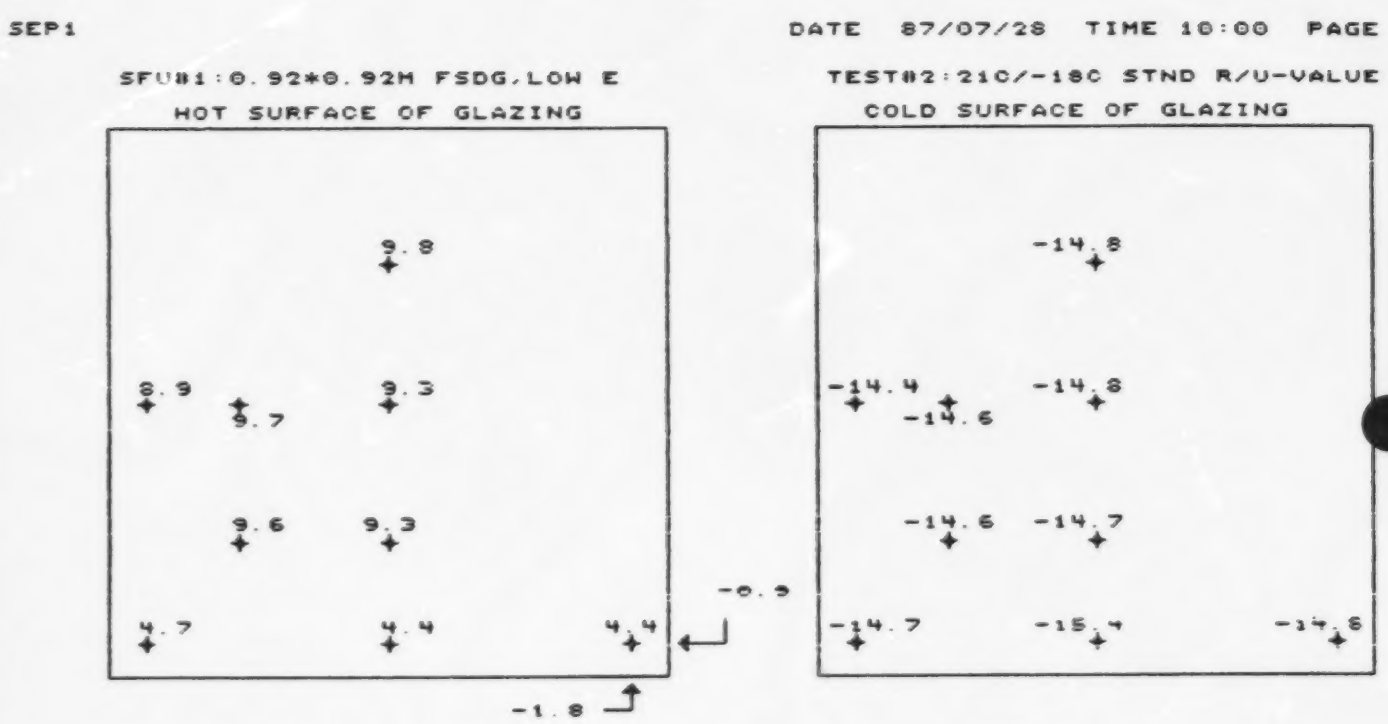


Figure 1.2

Glazing Unit #1: FSDG Unit with Low Emissivity Coating Temperatures
at Locations Shown on Figure 1.0
Test #1.2: 21°C/-35°C

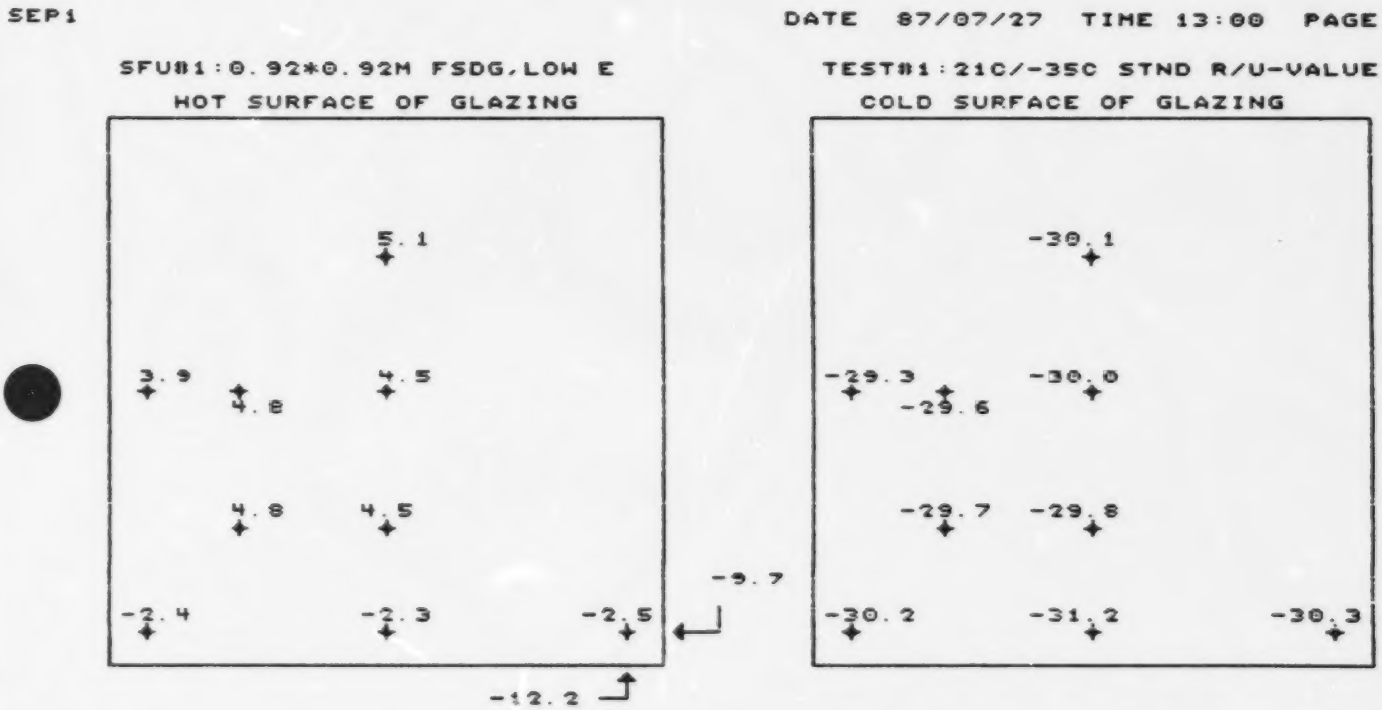


Figure 2.0

Room-side View of the Factory Sealed Double Glazed Unit #2 with Internal Electric Heater Showing the Locations of the Thermocouples and the Heater Leads.

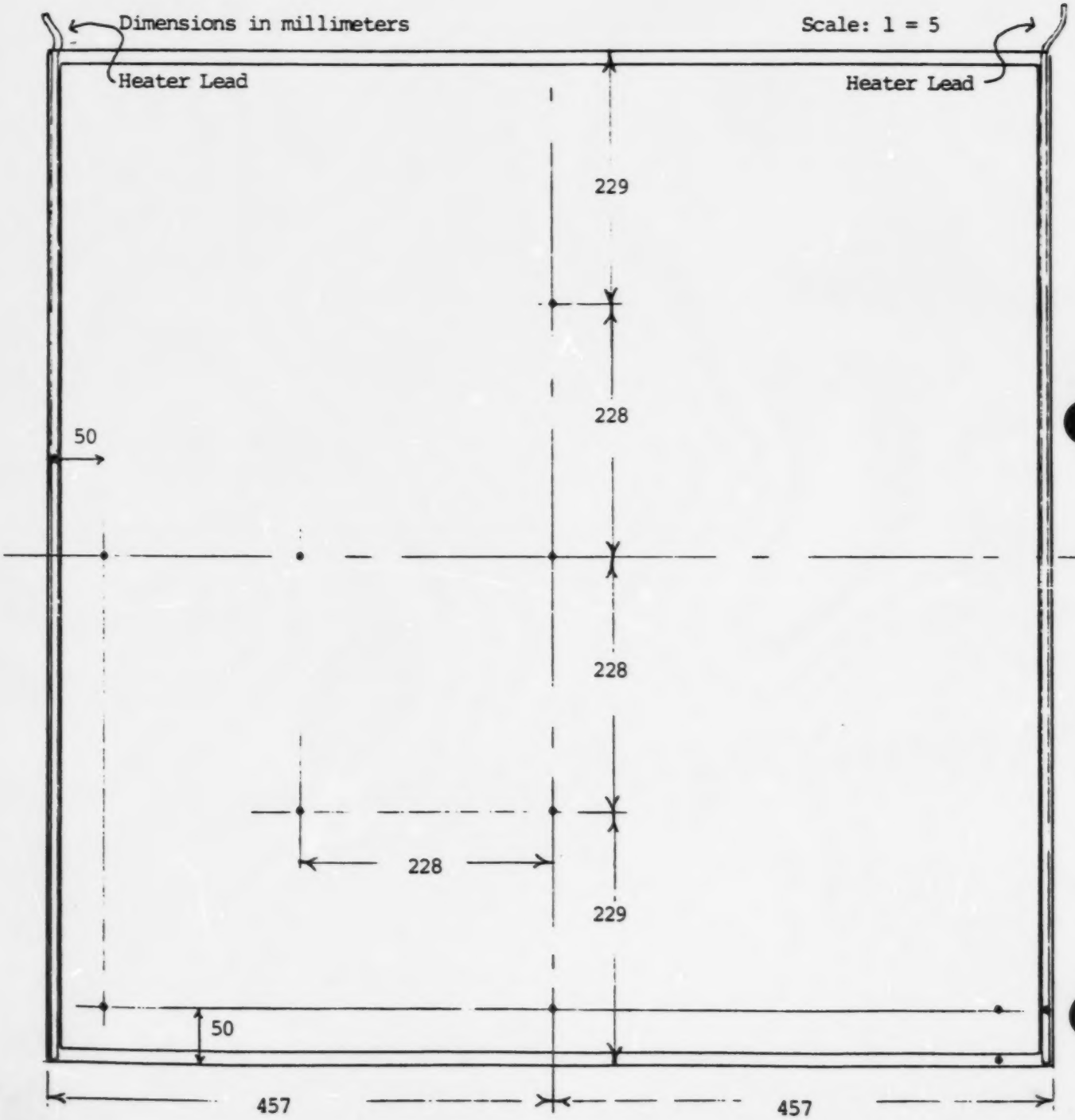
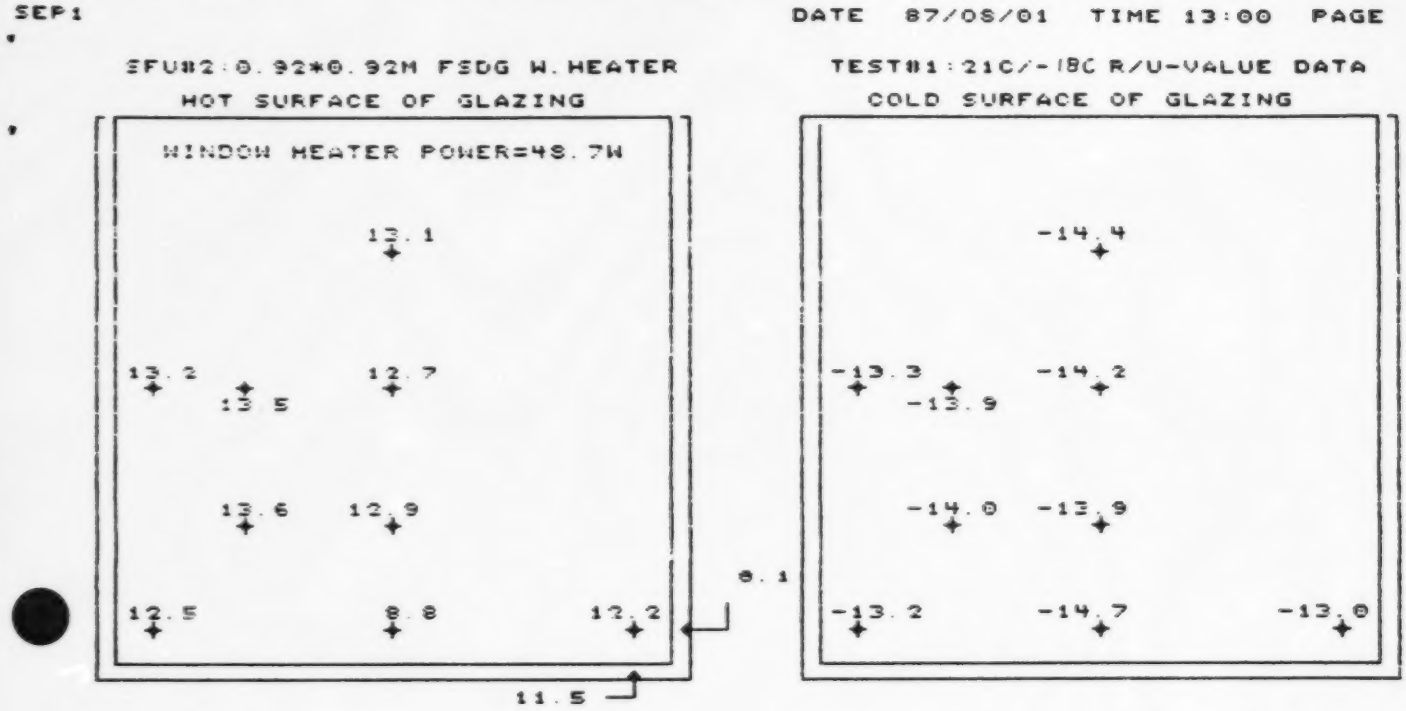


Figure 2.1

Glazing Unit #2: FSDG Unit with Internal Heater
Temperatures at Locations Shown on Figure 2.0

Test #2.1: 21°C/-18°C, Heater Power = 48.7W



SEP1 21°C/-18°C, No Heater Power

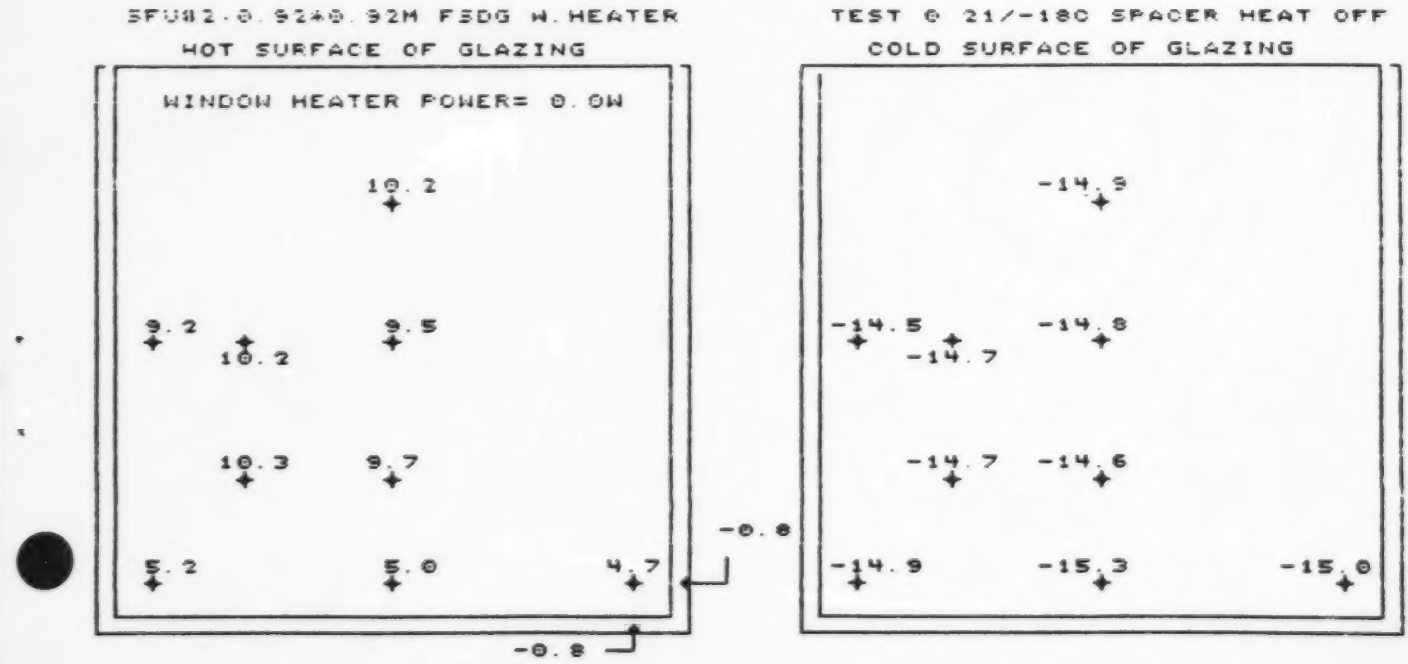
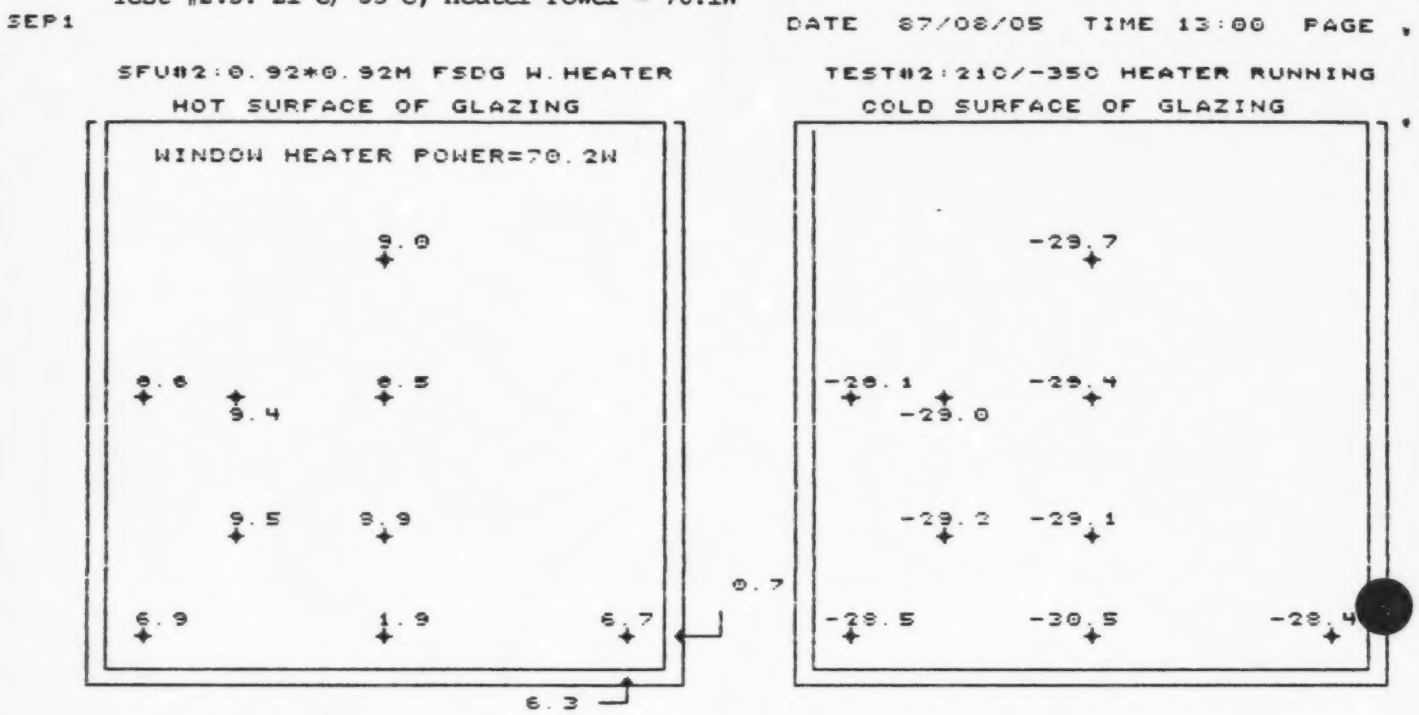


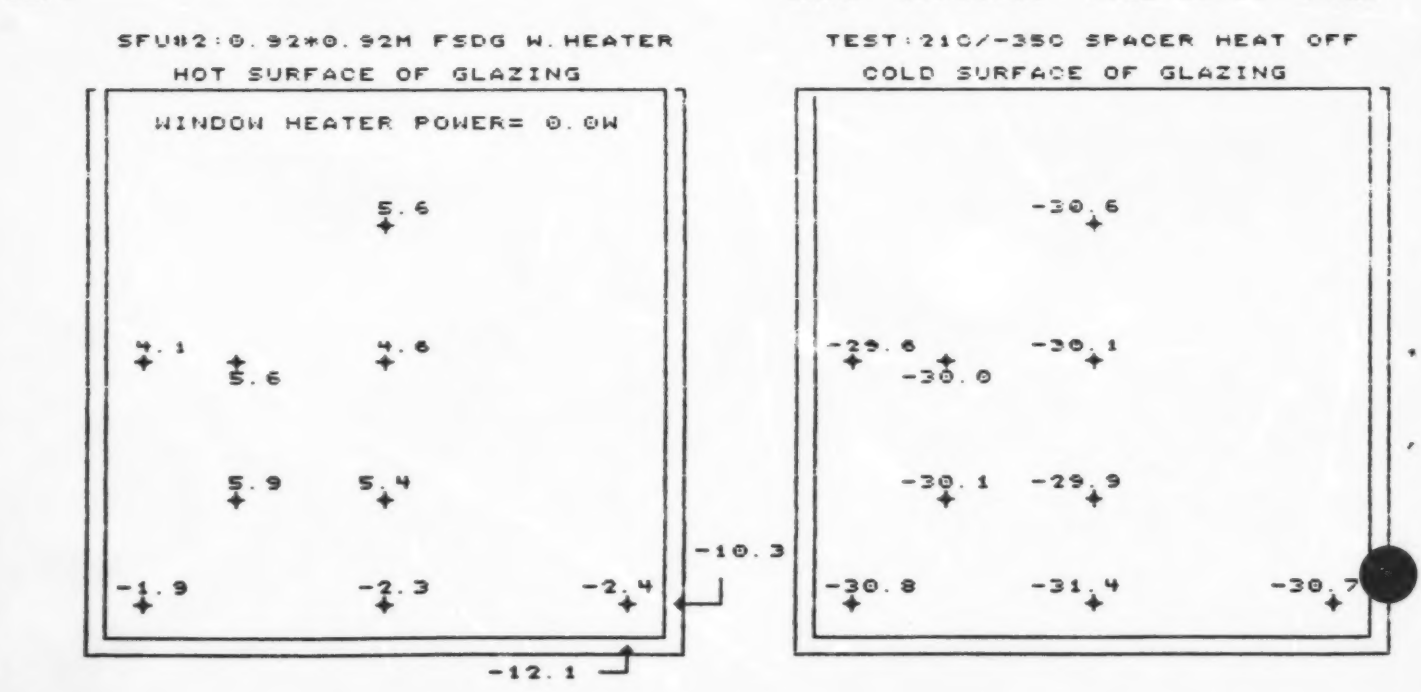
Figure 2.2

Glazing Unit #2: FSDG Unit with Internal Heater
Temperatures at Locations Shown on Figure 2.0

Test #2.3: 21°C/-35°C, Heater Power = 70.1W



21°C/-35°C, No Heater Power



APPENDIX A
TEST PROCEDURE AND CALORIMETER HEAT TRANSFER CHARACTERISTICS

1. Test Procedure

A steel frame was used to hold the test assembly consisting of a wall, referred to as the mask, and the test specimens. The mask was constructed of 95 mm extruded polystyrene insulation with 17 mm of plywood covering on the room side and weather side surfaces. The thermal resistance of the mask was determined in the Environmental Test Facility prior to making an opening for the test specimens. The mask, with a calibration specimen in the opening made for the test specimens, was calibrated using the same room side and weather side conditions as those to be used for the window specimens.

Subsequently, the test specimens were installed into the mask. The specimen was centered in the opening and sealed to minimize air leakage through the opening. Thermocouples were used to measure the room side and weather side surface temperatures on the mask as well as the surface temperatures on the specimen.

The test assembly of the specimens in the mask was mounted on the weather side chamber of the Environmental Test Facility. The calorimeter used to measure the heat flow through the test assembly was mounted over the room side surface of the test assembly. The room side chamber was joined to the weather side chamber.

2. Calorimeter Heat Transfer Characteristics

The general approach used to determine the heat transmission characteristics of the sealed glazing units is outlined in the paper "DBR's Approach for Determining the Heat Transmission Characteristics of Windows", by R.P. Bowen, BRN 234, IRC, Nov. 1985 (copy attached). In summary, the approach involves measuring the total power supplied to the calorimeter and deducting the heat transfer through the mask to arrive at the heat transfer through the specimen. From the specimen heat transfer, using the relationships for the radiation and convective heat transfer from the calorimeter to the specimen, the equivalent room side surface temperature of the specimen is calculated. The equivalent weather side surface temperature is also calculated from the specimen heat transfer and the air film provided by the wind machine. The thermal conductance, resistance, design thermal resistance and design coefficient of heat transmission are calculated.

The following is a summary of the equations used for the calculations

$$Q_T = Q_s + Q_m$$

where Q_T = total measured power supplied to the calorimeter

Q_s = is the heat transfer through the test specimen

Q_m = is the heat transfer through the mask.

In turn Q_s is given by

$$Q_s = Q_c + Q_r$$

and $$Q_c = A_1 C(T_h - T_1)^B$$

$$Q_r = A_1 \sigma \sum_{i=2}^{4} F_{1i} (T_i^4 - T_1^4)$$

where Q_c = convective component of the heat transfer from the calorimeter to the specimen

Q_r = radiative component of the heat transfer from the calorimeter to the specimen

T_h = the calorimeter air temperature

T_b = the baffle temperature

T_1 = the room side specimen surface temperature

F_{1i} = the interchange factor for radiation from surface 1 to the other surfaces:

i=2 for mask	$F_{12} = 0.051$
i=3 for baffle	$F_{13} = 0.691$
i=4 for calorimeter	$F_{14} = 0.097$

σ = the Stefan-Boltzmann constant = 5.6703×10^{-8} $(W/m^2 \cdot K^4)$

B and C are constants for the convective heat transfer to the specimen.

The constants B and C were established from the results of a series of tests using the same mask as used for the test specimens but with specially constructed calibration specimens 1.0 m x 1.6 m and 0.8 m x 1.0 m in place of the test specimens. The calibration test conditions were nominally the same as those for the test specimens; that is, 22°C Room side and -7°C, -21°C, and -35°C weather side temperatures. From the measurements with the calibration specimen and the conductance which was determined in the Thermal Conductivity Laboratory of IRC, Q_r was calculated and Q_c established for each set of conditions. A linear fit of the data yields values of B = 1.266 and C = 1.581 $W(m^2 \cdot K^{1.266})$.

$$\text{Thus } \frac{Q_s}{A_1} = q_s = q_r + q_c = 1.581 \cdot (T_h - T_1)^{1.266} + \sigma \sum_{i=2}^{4} F_{1i}(T_i^4 - T_1^4)$$

$$W/(m^2 \cdot K)$$

Once the mean surface temperature of the window is established, coefficients for the convective and radiative exchange, h_c and h_r, can be calculated:

$$h_c = 1.581\ (T_h - T_1)^{0.266} = q_c/(T_h - T_1)\ W/(m^2 \cdot K)$$
$$h_r = q_r/(T_b - T_1)\ W/(m^2 \cdot K)$$

The room side surface film coefficient, f_i, or inside film resistance R_{fi} is then

$$f_i = h_c + h_r \quad W/(m^2 \cdot K)$$
$$R_{fi} = \frac{1}{f_i} \quad m^2 \cdot K/W$$

The equivalent weather side surface temperature, T_2, is calculated by

$$T_2 = \frac{q_s}{f_o} + T_c$$

where

T_c = the weather side air temperature

f_o = weather side surface film established during calibration tests; 21.8 $W/(m^2 \cdot K)$ (weather side film resistance R_{fo} is then 0.05 $m^2 \cdot K/W$)

Expressions to Calculate Specimen R-value and U-value

The test specimen conductance, C and resistance R ($m^2 \cdot K/W$) are calculated by

$$C = q_s/(T_1 - T_2)\ W/(m^2 \cdot K);\ R = 1/C\ m^2 \cdot K/W$$

The values assigned to R_{fi} and R_{fo} in window design resistance values, R_D, are usually $R_{fi} = 0.12\ m^2 \cdot K/W$ and $R_{fo} = 0.03\ m^2 \cdot K/W$. The total specimen design resistance then becomes:

$$R_D = R + 0.12 + 0.03\ m^2 \cdot K/W$$

The design U-value; U_D is then:

$$U_D = 1/R_D\ W/(m^2 \cdot K)$$

APPENDIX B

1. Comments on the Heater Element of Glazing Unit #2:

The applicant requested that the voltage supplied to the internal heater of Glazing Unit #2 be limited to (or under) 40 Volts. Preliminary tests were conducted on the internal heater of the Glazing Unit #2 prior to installation in the Environmental Test Facility to determine the electrical resistance, power levels, and the variation of the electric resistance with temperature.

The electrical resistance of the heater, at ambient, was 34.3 Ohms. A thermocouple was mounted on the bottom of the unit, over the spacer. A General Radio Co. "Variac" was connected to the heater leads of the unit and power was applied without exceeding 30 Volts. After 20 minutes, the temperature at the sensor had risen from 20.8°C to 30.7°C. The power source was disconnected and the electrical resistance was measured at various temperatures:

- at 31.1°C, resistance was 29.1 Ohms
- at 26.1°C, resistance was 30.2 Ohms
- at 22.1°C, resistance was 30.7 Ohms
- at 21.1°C, resistance was 30.9 Ohms

The leads of the Hewlett Packard 3468A Multimeter were left connected overnight. The next morning the electrical resistance was 31.9 Ohms at 20.8°C. After mounting Glazing Unit #2 in the mask, the electrical resistance was back up to 34.1 Ohms. During Tests #2.1 and 2.2, the resistance value changed as follows:

- after 6 hours with power, resistance was 20.3 Ohms
- after 26 hours with 48 Watts, resistance was 19.5 Ohms
- after 24 hours with 70 Watts, resistance was 16.3 Ohms

Note: After the heater element had run for about 25 hours at 70 Watts, the resistance dropped from 16 to 12 Ohms in a few minutes and it was assumed the heater element was "shorted" to the aluminum window spacer.

2. Procedure for Supplying and Measuring Power to the Heater:
A Kepco Regulated DC Supply (Model KS36-5M) was used to supply power to the internal heater of Glazing Unit #2. A Guildline Resistor (Model 9221) and a Guildline Voltage Divider (Type 9716) were wired into the circuit to measure current and voltage, respectively.

3. Changes in Test Procedures for Glazing Unit #2:
The room side and weather side surface temperatures were calculated by an area-weighted averaging method using the measured temperatures of the thermocouples.

For Tests #2.1 and 2.2, the Heat Flow Through the Test Specimen (Q_s) is determined by subtracting the Heat Flow Through the Mask (Q_m) from the total Heat Flow Through the Test Assembly (Q_T) and then adding in the power supplied to the internal heater: $Q_s = Q_T - Q_m + Q$ of Internal Heater.